

**Clothe the Soldier Prototype K1 Load Carriage System  
Design Assessment using the APLCS Load Carriage Simulator**

by

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## **Abstract**

The objective of this study was to conduct a standardized assessment of the Cloth Soldier (CTS) Prototype K1 pack on a computerized Load Carriage (LC) Simulator to assess the load control and load transfer capability of the CTS K1 Pack. These aspects of pack design were comprised of displacement, force, moment and pressure variables that had been validated on previously tested systems where LC Simulator outputs were compared to assessments by experienced users during human trials.

A trial consisted of measuring inertial properties and dimensions, loading the pack with a 25 kg payload, and mounting the pack and balancing the moments. Output variables were: three dimensional motions of the pack's center of gravity relative to the person's motion; forces and moments from a 6 degree of freedom load cell at the level of the hips; and average and peak skin pressures and skin forces over the anterior and posterior shoulders, and upper and lower back. To examine the resistance of the pack frame to torso motions in three planes, a pack LC stiffness compliance tester was developed.

For load control, the CTS pack K1 ranked as superior in side to side, up and down and resultant (r) relative pack-person motions. All other load control variables were not significantly different from other systems. For load transfer, the CTS K1 pack was inferior for dampening average forces in the vertical direction (z). The CTS Prototype Pack K1 showed typical stiffness characteristics in torsion and in lateral bending. It also demonstrated superior forward flexion stiffness which is correlated to good combined functional ratings where large movements are required, reduced posterior neck discomfort and reduced lower back discomfort.

## Résumé

Le but de la présente étude était de mener une évaluation standardisée du prototype de sac à dos HLS K1 sur un simulateur de transport de charge informatisé afin d'évaluer la capacité de contrôle et de transfert de charge de ce sac à dos. Ces aspects conceptuels de sac à dos comprenaient des variables de mouvement, de force, de moment et de pression qui avaient été validées sur des systèmes déjà mis à l'épreuve où les résultats du simulateur de transport de charge étaient comparés aux évaluations faites par des utilisateurs expérimentés lors d'essais avec des humains.

Un essai consistait à mesurer les propriétés d'inertie et de dimensions avec une charge utile de 25 kg sur le sac à dos, en montant ce sac à dos et en équilibrant ses moments. Les variables de sortie étaient les suivantes : mouvements sur trois dimensions du centre de gravité du sac à dos par rapport aux mouvements de la personne; les forces et les moments par rapport à une cellule dynamométrique tridimensionnelle à 6 degrés de liberté au niveau des hanches; pressions moyennes sur la peau, pressions de crête et forces sur l'avant et l'arrière des épaules, ainsi que le haut et le bas du dos. Pour évaluer la résistance de l'armature externe aux mouvements du torse sur trois plan, on a mis au point une unité de vérification de la conformité de transport de charge.

En ce qui concerne le contrôle de la charge, le sac à dos CTS K1 a obtenu une note supérieure pour les mouvements d'un côté à l'autre (x) pour les mouvements verticaux (z) et la résultante (r) pour les mouvements relatifs entre le sac à dos et une personne. Les autres variables de contrôle de charge ne présentaient aucune différence sensible par rapport aux autres systèmes. En ce qui concerne le transfert de charge, le sac à dos K1 s'est révélé inférieur pour amortir les forces moyennes sur le plan vertical (z). Ce prototype de sac à dos K1 HLS a démontré des caractéristiques de rigidité typiques pour la torsion et la flexion latérale. Il a également démontré une rigidité supérieure en flexion vers l'avant qui correspondait à un bon taux de fonctionnalité lorsque des mouvements à grande amplitude sont nécessaires, ainsi qu'à une réduction de l'inconfort à l'arrière du cou et au bas du dos.

## Executive Summary

The objective of this study was to conduct a standardized assessment of the Cloth Soldier (CTS) Prototype K1 pack on a computerized Load Carriage (LC) Simulator to assess the load control and load transfer capability of the CTS K1 Pack. These aspects of pack design were comprised of displacement, force, moment and pressure variables that had been validated on previously tested systems where LC Simulator outputs were compared to assessments by experienced users during human trials.

The LC Simulator consisted of interchangeable anthropometrically weighted manikins (50<sup>th</sup> percentile male used) which were covered with a skin-like surface, driven by computer controlled pneumatic actuators programmed to create a walking displacement pattern of  $\pm 25.4$  mm amplitude and 1.8 Hz frequency. A trial consisted of measuring inertial properties and dimensions, loading the pack with a 25 kg payload, and mounting the pack and balancing the moments. Five intervals of 10 seconds of data were recorded over a 1200 second period. By this approach, the pack was assessed on the initial setup and after a sustained period of walking. Output variables were: three dimensional motions of the pack's center of gravity relative to the person's motion; forces and moments from a 6 degree of freedom load cell at the level of the hips; and average and peak skin pressures and skin forces over the anterior and posterior shoulders, and upper and lower back.

To examine the resistance of the pack frame to torso motions in three planes, a pack LC stiffness compliance tester was developed. The LC stiffness compliance tester consisted of a two-piece anatomical human trunk model (50<sup>th</sup> percentile male) which was designed to move in one plane at a time. Using a load cell and precision potentiometer, pack resistance to forward flexion, lateral bending and torsion were evaluated.

The CTS Prototype Pack K1 was compared to previously validated variables for load control and load balance from the LC Simulator. Results were expressed in comparison to the mean value, superior deciles (best 10%) and inferior deciles (worst 10%) values. For load control, the CTS pack K1 ranked as superior in side to side, up and down and resultant (r) relative pack-person motions. All other load control variables were not significantly different from other systems. For load transfer, the CTS K1 pack was inferior for dampening average forces in the vertical direction (z). The main design concern was the large forces applied to the

skin surface at the level of the upper lumbar spine. Based on previous correlational data, the CTS Prototype Pack K1 is substantially inferior to other systems since 93.2 N far exceeds the average of other systems (22.96 N). This value is only slightly less than the recommended design limit for transverse force on the lumbar spine (135 N).

## Sommaire

Le but de la présente étude était de mener une évaluation standardisée du prototype de sac à dos HLS K1 sur un simulateur de transport de charge informatisé afin d'évaluer la capacité de contrôle et de transfert de charge de ce sac à dos. Ces aspects conceptuels de sac à dos comprenaient des variables de mouvement, de force, de moment et de pression qui avaient été validées sur des systèmes déjà mis à l'épreuve où les résultats du simulateur de transport de charge étaient comparés aux évaluations faites par des utilisateurs expérimentés lors d'essais avec des humains.

Le simulateur de contrôle de charge consistait en mannequins interchangeables lestés de manière anthropométrique (modèle utilisé correspondant au 50<sup>e</sup> percentile des hommes), munis d'une surface pelliculaire et contrôlés par des actionneurs pneumatiques qui sont commandés par ordinateur et programmés pour susciter un schéma de marche d'une amplitude de  $\pm 25,4$  mm et d'une fréquence de 1,8 Hz. Un essai consistait à mesurer les propriétés d'inertie et de dimensions avec une charge utile de 25 kg sur le sac à dos, en montant ce sac à dos et en équilibrant ses moments. Cinq intervalles de 10 secondes de données ont été enregistrés pendant une période de 1 200 secondes. On évaluait de cette manière le sac à dos sur le montage initial et au bout d'une période soutenue de marche. Les variables de sortie étaient les suivantes : mouvements sur trois dimensions du centre de gravité du sac à dos par rapport aux mouvements de la personne; les forces et les moments par rapport à une cellule dynamométrique tridimensionnelle à 6 degrés de liberté au niveau des hanches; pressions moyennes sur la peau, pressions de crête et forces sur l'avant et l'arrière des épaules, ainsi que le haut et le bas du dos.

Pour examiner la résistance de l'armature externe du sac à dos afin de contrôler les mouvements de la charge sur trois plans, on a mis au point une unité de vérification de la conformité de transport de charge. Cette unité se composait d'un modèle anatomique de tronc humain (correspondant au 50<sup>e</sup> percentile des hommes) qui était conçu pour limiter les réactions sur un plan de mouvement à la fois. À l'aide d'une cellule dynamométrique et d'un potentiomètre de précision, la résistance du sac à dos à la flexion/extension, la flexion latérale et la torsion ont également fait l'objet d'une évaluation.

Le prototype de sac à dos HLS K1 a été comparé à des variables déjà validées pour le contrôle l'équilibre de la charge sur le simulateur de contrôle de charge. Les résultats ont été exprimés par comparaison à la valeur moyenne, et aux valeurs déciles supérieures (le décile le plus élevé) et inférieures (le décile le plus faible). En ce qui concerne le contrôle de la charge, le sac à dos CTS M1 a obtenu une note supérieure pour les mouvements d'un côté à l'autre, les mouvements verticaux et les mouvements relatifs résultants (r) entre le sac à dos et une personne. Les autres variables de contrôle de charge ne présentaient aucune différence sensible par rapport aux autres systèmes. En ce qui concerne le transfert de charge, le sac à dos K1 s'est révélé inférieur pour amortir les forces moyennes sur le plan vertical (z). La préoccupation principale concernant sa conception étaient les forces importantes appliquées sur la surface de la peau au niveau supérieur du rachis lombaire. En se fondant sur des données corrélationnelles, le prototype de sac à dos K1 HLS est sensiblement inférieur aux autres systèmes puisque une force de 93,2 N dépasse de loin la moyenne des autres systèmes (22,96 N). Cette valeur n'est que légèrement inférieure à la limite nominale recommandée pour les forces transversales sur le rachis lombaire (135 N).

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## **1.0 Scope of Report**

### **1.1 Objectives of Test**

The two main areas of interest when investigating load carriage are load control and load transfer. Proper load control is necessary for the user to maintain balance and mobility during load carriage. Relative displacement between user and the load carriage system, rotational moments generated during load carriage, and resistance of the LC system to deflections within the range of human motion, are quantification tools used to define the load control ability of a load carriage system. Capacity for load carriage, muscle fatigue during carriage, and risk of tissue injury are all dependent on load transfer to the user. Measurement of skin contact pressures, specifically in significant load bearing areas, and forces applied by the load allows for an increased understanding of load transfer in LC systems.

### **1.2 System Evaluated**

Testing of the CTS Prototype Pack K1, performed by the Ergonomics Research Group at Queen's University, included measurement of the following variables:

1. Shoulder strap and waist belt tension.
2. Relative displacement between LC system and torso.
3. Hip reaction forces.
4. Hip reaction moments.
5. Skin contact pressures in five regions.
6. Torsional pack stiffness.
7. Lateral pack stiffness.

Comparison of the results from previous LC system tests with those of the CTS Pack K1 was also performed, allowing for comparison of design features and evaluation of system strong points.

## **2.0 Methods**

### **2.1 LC Simulator**

#### **2.1.1 Torso Specifications and Preparation**

A family of four anthropometric mannikins (5<sup>th</sup> and 50<sup>th</sup> percentile females, and 50<sup>th</sup> and 95<sup>th</sup> percentile males, as defined by Safework™ anthropometric software) were constructed for LC simulator testing. Each mannikin was comprised of a head and trunk section, with arms truncated in the mid-humeral region and legs extending to just below the buttocks.

These human models consisted of a fiberglass outer shell with an expandable poured polyurethane foam filling. Proper mass distribution was achieved by thoroughly mixing aggregate with the interior foam. A vertical cylindrical cavity was created in each mannikin to allow for mounting of a 6 degree-of-freedom load cell. In each case, the neutral axis of the load cell was positioned at the approximate location of the mannikin's hips. This load cell was further mounted on a single axis articulating vice, which permitted the mannikin and LC system to be placed in a balanced anterior body lean position for load carriage. Finally, the surface of each mannikin was covered with a 5 mm thickness of Bocklite™, a synthetic skin-like material used on prosthetics, to approximate the compressive response of human skin over bone. For all tests, the mannikin was dressed in a Canadian Forces standard issue combat shirt.

#### **2.1.2 LC System Loading and Mass Properties**

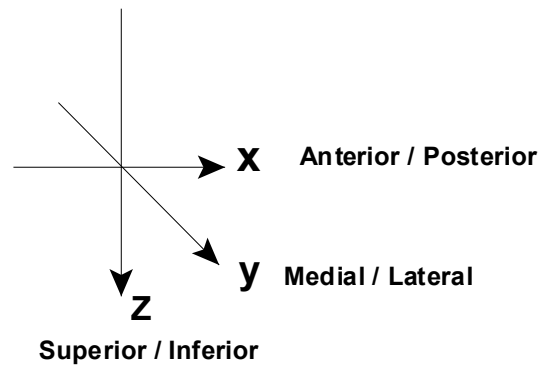
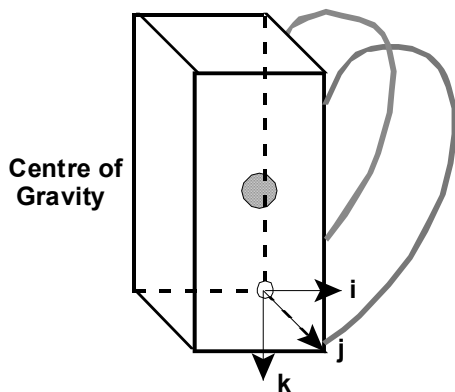
LC payload was created by locating a block of mass at the center of the system volume. The mass used in the LC system was 25 kg +/- 1 kg and was comprised of rectangular steel plates. These plates were held in position by a rigid polystyrene foam shell which filled the LC volume. Three dimensional location of the LC system center of gravity and LC system moments of inertia about the three pack axes are available in Table 2.1 for the pack with payload. Mass of the pack, unloaded and loaded, is also included.

**Table 2.1** Mass properties of load carriage system.

Total mass for both the unloaded and the loaded LC system, location of the center of gravity in three dimensions, and the physical dimensions of the LC system are all included.

Load Carriage System: CTS Prototype Pack K1			
<b>Mass:</b>	<b>LC System only</b>	3.4	(kg)
	<b>LC System w/ load</b>	29.5	
<b>Physical Size:</b>	<b>Length (k)</b>	590.0	(mm)
	<b>Width (j)</b>	390.0	
	<b>Depth (i)</b>	275.0	
<b>Center of Gravity* :</b>	<b>Height (k)</b>	331.3	(mm)
	<b>Width (j)</b>	190.0	
	<b>Depth (i)</b>	127.0	

\* - all C of G measurements are relative to the lower left corner of the LCS as it is worn.



### 2.1.3 Test Protocol

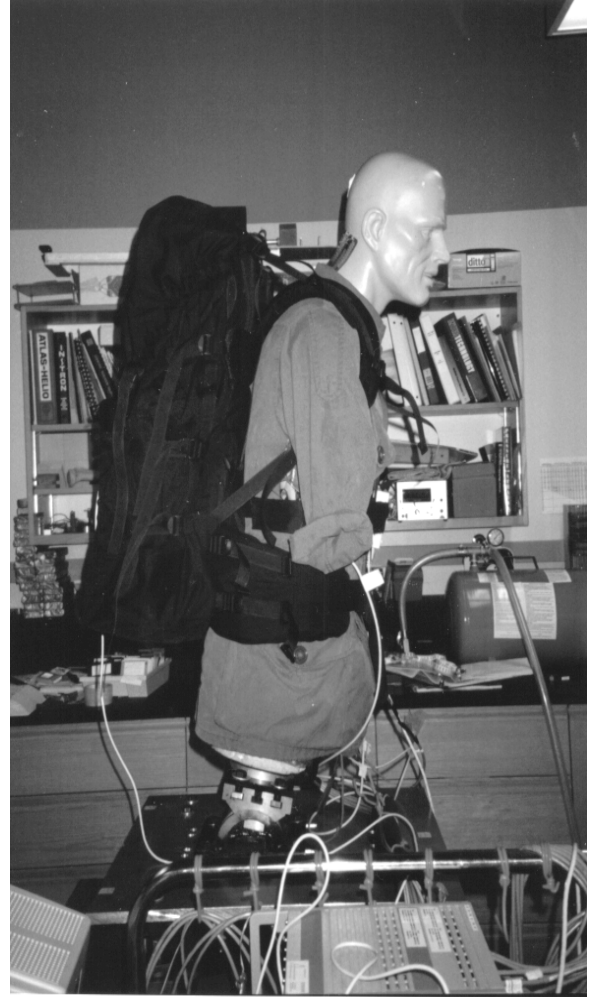
The LC Simulator (Figure 2.1.1) consists of the previously described rigid mannikin, mounted on a programmable displacement platform. This platform rests on three air cylinders which allows vertical motion as well as rotation about the x (anterior/posterior) and y (medial/lateral) axes. A computer controlled vertical displacement pattern ( $\pm 25.4$  mm amplitude, 1.8 Hz frequency) simulated marching, and linear displacement transducers provided positional information for the control system. Feedback control was accomplished by varying the differential pressure across each cylinder face.

The duration of one LC System test was 1200 seconds, with data recorded at 10 seconds (initial data set), and at each 300 second interval. Sampling rate for all data collection was 55 Hz and the duration was 10 seconds (minimum). The outcome measures from the LC system tests consisted of the relative displacement between mannikin and marching order system, skin contact pressures on the shoulders, upper back, lower back, and hip reaction forces and moments. The following sections describe the methodology and instrumentation used to collect LC System characteristic data.

### 2.1.4 Strap Forces

During the setup phase of the LC Simulator testing, strap force tension transducers were placed in-line in the right lower shoulder strap and the right half of the waist belt, free of any hip/kidney padding. Attachment of the transducers was accomplished by placing a pin through an attachment ring in the end of the carrier material of each transducer, ensuring that all tension in the strap was transmitted through the transducer. Output from the force transducers was received and amplified by a Keithley MetraByte DATAQ system (Keithley MetraByte Instruments Incorporated). Initial settings of  $55 \pm 5$  N in the shoulder strap and  $40 \pm 5$  N in the waist strap were used for all load carriage trials.

The force transducers were constructed with four foil style strain gauges, attached in a full Wheatstone bridge configuration to a rounded I-shaped 6061-T6 aluminum carrier with a length of 38.00 mm and thickness of 1.14 mm. Static testing of the transducers showed they were highly linear ( $r^2 > 0.9995$ ) with a small standard error ( $< 0.01$  V) (Stevenson, JM., et al, 1996).



**Figure 2.1.1.** Photograph of CTS Prototype Pack K1 positioned on LC simulator mannikin

### 2.1.5 Relative Displacement of LC System and Torso

An electromagnetic position tracking system (Fastrak™ by Polhemus Incorporated) was used to provide three dimensional displacement data. The source for the Fastrak™ was affixed with nylon screws to the underside of the left arm of the mannikin. A Fastrak™ sensor was also attached in a secure position to the superior polystyrene surface of the LC System payload. Displacement data, for the payload with respect to the source, was recorded for 10 seconds at 55 Hz every 300 seconds over the duration of the test. Translation from the superior payload sensor location to the loaded pack center of gravity was performed to provide estimated displacement vectors between the center of gravity of the loaded LC system and the mannikin.

Increased displacement of the LC system, with respect to the soldier, can cause decreased agility due to reduced load control. Unrestrained displacement of marching order kit and LC equipment also leads to stability problems and local discomfort due to repeated collisions between the soldier and items.

Direct comparison of Fastrak™ positional data with data collected from an opto-electric positional recording system (Optotrak™ by Northern Digital Incorporated) with high precision (RMS error <0.01 mm) provided an RMS error for Fastrak™ data of 0.65 mm.

### 2.1.6 Reaction Forces and Moments

Ground reaction forces and moments were collected using a 6 degree-of-freedom load cell (AMTI Incorporated) based on a body fixed coordinate system located at the hip and oriented along the long axis of the trunk. The outcomes from this instrumentation were reported as a resultant mean force (N), in which reaction forces in the Fx (forward and back), Fy (side to side), and Fz (up and down) were combined vectorially. Similarly, a resultant mean moment (Nm) was defined in which the moments Mx (lateral), My (flexion/extension), and Mz (torsional) were components. Two factors affect the moments and forces transmitted through the load cell: motion and mass of the moving bodies. In the LC simulator, the mass of the torso requires a significant reaction under the imposed displacement from the positioning actuators. This is in addition to the reactions needed to move the payload itself. To compensate for these

effects, a two-step procedure is used. First, an initial run of the 50<sup>th</sup> percentile male mannequin with no load carriage system in place is used to generate a baseline of reaction moments and forces. These values are then subtracted from the results of a run in which a load carriage system is being evaluated.

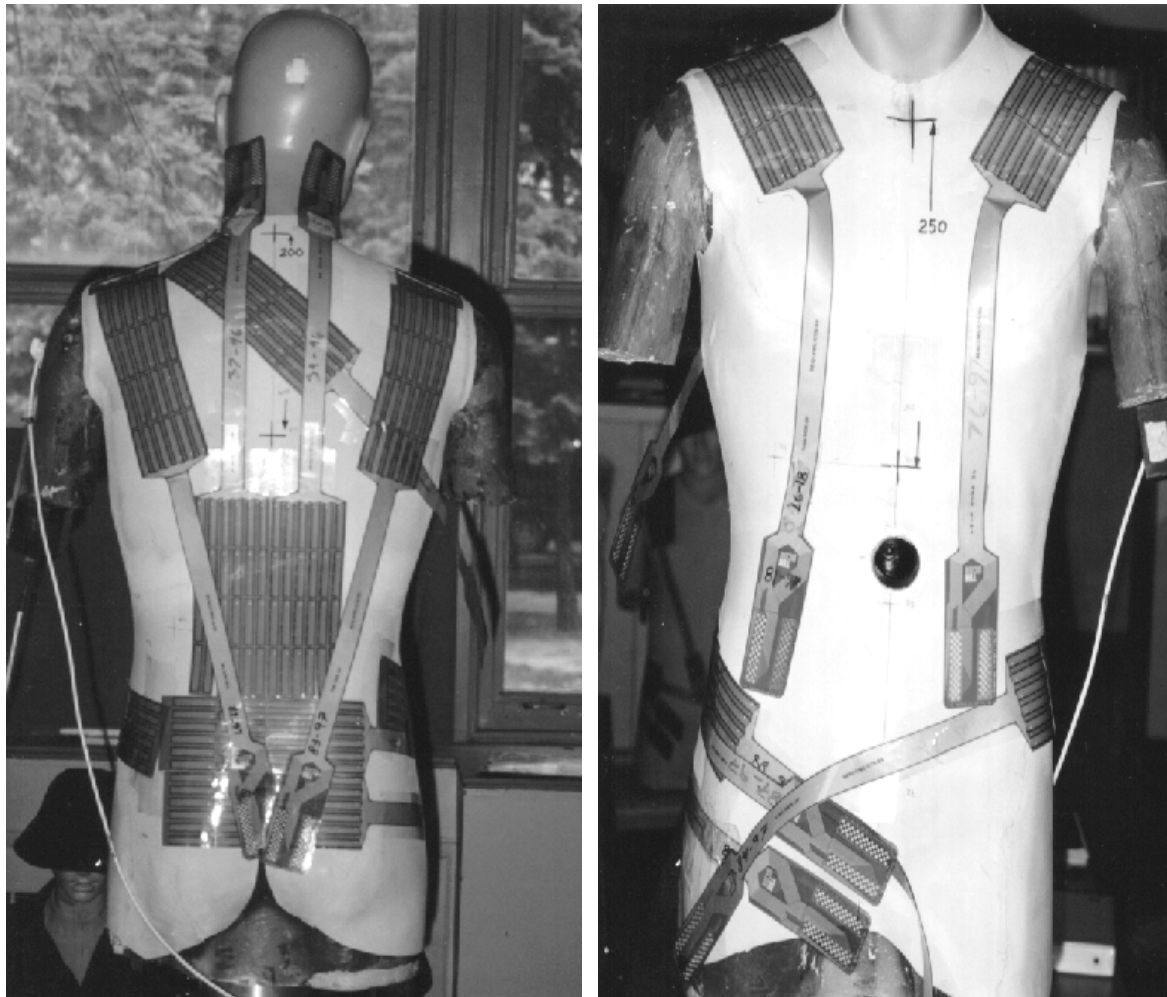
The second step is to normalize the reaction values by dividing them by the total payload of the system. The payload is the sum of the pack load, the weight of the pack itself, the weight of additional load carriage devices (such as webbing or vests), and the weight of clothing.

The resultant *normalized* values are expressed as Nm/kg for moments and N/kg for forces. This method of normalization is typical for biomechanical measurements. A normalized force of 9.81 N/kg indicates a force of 9.81 newtons acts for each kilogram of load carried. This is equivalent to the weight of the payload and is sometimes expressed “1 x Payload Weight”. A normalized force of 12.2 N/kg, for example, would be expressed as  $12.2/9.81 = 1.24 \times \text{Payload Weight}$ .

Reaction forces represent the force that a person must provide at the hip to counter balance any off center forces resulting from the load carriage system and contents. Similarly, the net reaction moments reflect the magnitude of counter balancing needed by muscles above the hips to offset any rotation created during normal gait, or by the forcing function of the simulator. In both cases, the greater the muscle force needed to maintain balance, the greater the soldier fatigue, both locally and overall, leading to discomfort and pain.

#### 2.1.7 Skin Contact Pressures

An F-Scan<sup>TM</sup> pressure sensor system (Tekscan Incorporated) was used to acquire contact pressure data on the mannikin skin over the anterior shoulder and posterior scapula areas, as well as in the lower back region. Figure 2.1.2 shows the orientation of the F-Scan<sup>TM</sup> 9810 pressure sensors, which were affixed to the mannikin with a non-permanent spray adhesive. The F-Scan<sup>TM</sup> system uses a matrix of force sensitive resistors, which are arranged in a rectangular pattern and



**Figure 2.1.2.** LC Simulator mannikin, with F-Scan™ pressure sensors in place.

contained between two flexible polyester plastic sheets. At full size there are 96 force sensitive resistors, spaced over a region 206 mm by 76 mm. When the thin polymer foil in an element is compressed, the voltage passed across the element changes. This change is sensed by system software, and is recorded as a load normal to the sensor surface, based on individual calibration for each sensor. Information is transferred to the computer through a signal processing unit and cable to a computer card. This information can be replayed in 'movie' format, which can give a dynamic measurement of force, average and peak pressures, active area, or duration of contact. Previous testing at Queen's (DCIEM Contract #W7711-4-7225/01-XSE) has found the F-Scan™ system standard error of the mean to be 9.6 % for average pressures and 14 % for peak pressures. Also, use of the sensors on a curved surface leads to a 9% standard error of the mean for average pressure results (MacNeil, SK., 1996).

For LC system testing pressure data was reported in terms of peak dynamic pressures (kPa) and average pressure over all active cells of the sensors (kPa) in the anatomical areas of interest; anterior shoulder, posterior shoulder (scapula), hip, and lower back. Research has shown that blood occlusion can occur when tissues are loaded at an average pressure of 14 kPa for 8 hours (Holloway, JA., et, 1976). Average skin contact pressures of 20 kPa have also been associated with discomfort in 95 % of a test sample.

## **2.2 LC Compliance Stiffness Tester**

### **2.2.1 Torso Specification and Preparation**

A pack compliance stiffness tester was developed to allow the placement of each load carriage system onto a two-piece anatomical human trunk model (50<sup>th</sup> percentile male). The model was custom-fitted with a layer of compliant synthetic skin, 5mm thick Bocklite. The upper torso portion of the model was free to rotate about a horizontal axis (y-axis for forward bending or x-axis for lateral bending) on two oil impregnated metal powder sintered bearings at the L3/L4 location of the human spine, or about the vertical axis (z-axis for torsional twisting) on a thrust bearing at the L4/L5 location. Only one degree of freedom was active for each type of test, with the other degrees of freedom mechanically locked. The lower waist portion of the model was rigidly fixed in an upright standing position to the steel support frame.

### 2.2.2 Test Protocol

Empty load carriage systems were used in this test to generate baseline LC system stiffness values, without the increased pack stiffness due to kit items. Each pack was placed in position on the model and all straps were securely fastened. Using in-line force transducers, the shoulder straps and the hip/waist strap were pre-tensioned to 55 N and 40 N respectively. The same settings were used in the load carriage simulator tests.

During each test run, analog signals from the two load cells and two potentiometers were captured using a data acquisition system (Keithley MetraByte Instruments Incorporated) in a portable personal computer at a sampling rate of 5Hz over a three minute period. Each data set was saved electronically on the hard drive for post-processing. A spreadsheet was used to post-process the data, each data set was partitioned into the first cycle and repeated cycles. Only the loading phase of each test cycle was analyzed. Load cell data was filtered first by averaging over a one or two degree interval of rotation and further averaged over two to four repeated test runs. For the forward and lateral bending tests, the upper torso inertia causes an apparent resistance against the bending motions. Baseline reference tests were established for the setup (upper torso without pack or clothing equipment) and a baseline correction was applied to the data sets by subtraction. For the torsional twisting tests, upper torso response had an insignificant effect on the torque transducer output and the baseline correction was not applied. The information was reduced to bending moments or torque about the hinge in Nm and relative rotation in degrees to produce characteristic moment-rotation curves for each pack configuration. Linear regressions were performed on each LC system data set to obtain an aggregate pack stiffness (slope of linear regression).

### 2.2.3 Torsional Stiffness

For the torsional twisting tests, load/torque was applied in the form of a horizontal force acting on a moment arm of 0.137m. This was achieved by means of a cable wrapped around a 0.273m diameter pulley on the overhead load transfer assembly (LTA). A modified trailer winch (Fulton Performance Products Incorporated) fitted with a multi-turn precision potentiometer (Bourns Electronics) was used to generate and measure rotation of the upper torso relative to the

waist section of the trunk model. A strain gauged torsion load cell was installed on the drive shaft to measure pack resistance against such rotations. Studies have shown that the average relative angle of twist during walking is approximately 18 degrees full scale which is  $\pm 9$  degrees about the neutral axis<sup>1</sup>. A value of 12 degrees from neutral was used as the maximum for testing. Load was applied manually with the trailer winch in a 60 second test cycle (25s ramp up, 10s hold, 15s ramp down, and 10s hold) in order to minimize inertial loads from the trunk model. Each test included three test cycles before adjustments were made to the setup (straighten clothing, tighten straps, position pack) and testing was repeated to ensure reproducibility.

#### 2.2.4 Forward and Lateral Stiffness

Load/moment was applied in the form of a horizontal force acting on a moment arm of 0.927m. This was achieved by means of two opposing cables attached to the LTA on a roller track. Each cable was pre-tensioned by a 5 kg mass to maintain proper alignment. An in-line tension transducer, similar to those used in the measurement of strap forces during LC simulator testing, was installed between the loading cable and the LTA to measure cable tension fluctuations during each load cycle. A second trailer winch fitted with a potentiometer was used to induce and measure the horizontal displacement of the LTA. Maximum excursion of the LTA was 1.035m resulting in a forward bending angle of 48 degrees. For the lateral bending tests, the anatomical trunk model was rotated 90 degrees vertically about the base while keeping the bearing assembly in its original orientation with respect to the LTA. For the lateral bending tests, excursion of the LTA was reduced to a maximum of 0.305m, resulting in a maximum lateral bending angle of 18 degrees. The normal range expected during walking/marching gait is about 2-7 degrees<sup>2</sup>.

### 3.0 Results

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<sup>1</sup> Rose, J., and JG. Gamble. (1994). **Human Walking - 2<sup>nd</sup> Edition**. (Williams and Wilkins, Baltimore, Maryland, USA.), pp. 263.

<sup>2</sup> Ibid, pp. 263.

### 3.1 LC Simulator Part 1 - Displacements and Forces

#### 3.1.1 Strap Forces

The mean tension for the lower right shoulder strap and the right waist belt for one test with the CTS Prototype Pack K1 are presented in Table 3.1.1. The full data set for one trial is included in Annex 3.1.

**Table 3.1.1** Shoulder strap and waist belt tension for the CTS Prototype Pack K1. The mean tension in these two suspension elements, along with the standard deviation, is presented.

	<b>Tension (N)</b>	<b>SD (N)</b>
<b>Shoulder Strap</b>	79	8
<b>Waist Belt</b>	44	6

#### 3.1.2 Displacements

The relative displacement data for the LC System is available in Table 3.1.2. Annex 3.1 contains the entire data set for the test trial. Range is defined as the difference between the minimum and maximum displacement, in one axis, measured over a 10 second sampling interval.

**Table 3.1.2** Relative displacement between pack and torso. Motions in x, y, and z directions were combined vectorially to produce a resultant displacement. Ranges and corresponding standard deviations are indicated.

	<b>Range (mm)</b>	<b>SD (mm)</b>
<b>X</b>	1.0	0.20
<b>Y</b>	4.1	0.88
<b>Z</b>	2.0	0.51
<b>R</b>	4.7	1.04

### 3.1.3 Reaction Forces

Table 3.1.3 contains the mean normalized reaction forces, as well as mean total reaction forces and standard deviations in all three axis, for one test trial with the CTS Prototype Pack K1. The full data set is also available in Annex 3.1.

**Table 3.1.3** Reaction forces for LC system testing.  
Forces in x,y, and z directions were combined vectorially to produce a resultant force (r).  
Mean normalized forces, total forces, and standard deviations for one trial are presented.

	<b>Normalized Force (N/kg)</b>	<b>Force (N)</b>	<b>SD (N)</b>
<b>X</b>	6.8	200.0	47.0
<b>Y</b>	-0.2	-6.0	18.0
<b>Z</b>	9.2	803.0	265.0
<b>R</b>	11.4	827.6	269.7

Normalized and mean force amplitudes.

	<b>Normalized Force Amplitude (N/kg)</b>	<b>Force Amplitude (N)</b>
<b>X</b>	3.5	102.0
<b>Y</b>	1.1	32.0
<b>Z</b>	6.2	447.5
<b>R</b>	7.2	460.1

### 3.1.4 Reaction Moments

Table 3.1.4 contains the average normalized reaction moments, in all three axis, for one test trial with the CTS Prototype Pack K1. Total reaction forces and standard deviations are

included in the table, and Annex 3.1 contains the full data set for the trial.

**Table 3.1.4** Reaction moments for CTS Prototype Pack K1 testing. Mean normalized moment, mean reaction moment, and standard deviation are presented in all three dimensions. Resultant moment (r) was the vectorial combination of the axial moments.

	<b>Normalized Moment (N.m/kg)</b>	<b>Moment (N.m)</b>	<b>SD (N.m)</b>
<b>X</b>	0.1	2.0	8.0
<b>Y</b>	-0.2	-6.0	20.0
<b>Z</b>	-0.1	-1.0	7.0
<b>R</b>	0.2	6.4	22.6

Normalized and mean moment amplitudes.

	<b>Normalized Moment Amplitude (N.m/kg)</b>	<b>Moment Amplitude (N.m)</b>
<b>X</b>	0.4	11.5
<b>Y</b>	1.4	41.0
<b>Z</b>	0.2	4.5
<b>R</b>	1.5	42.8

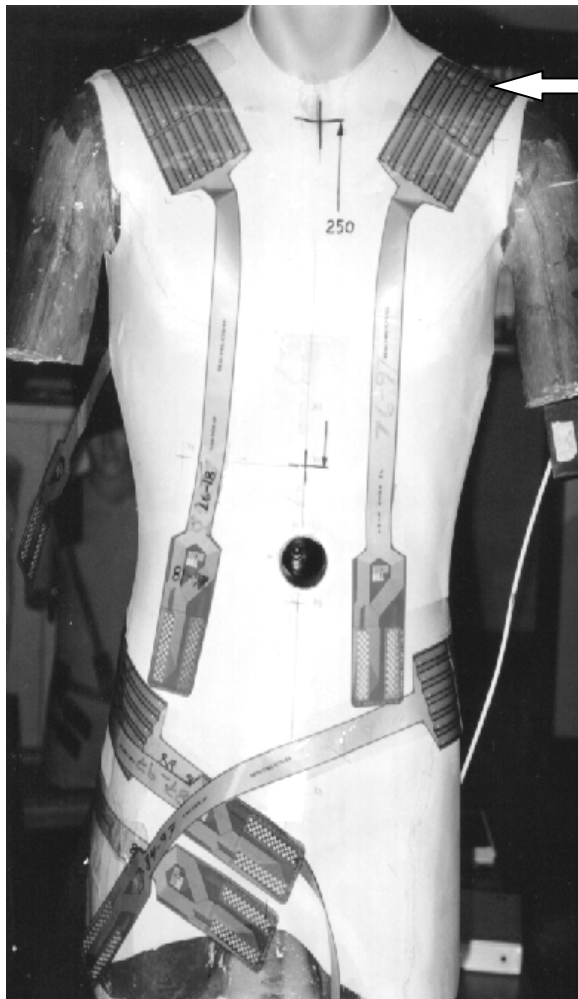
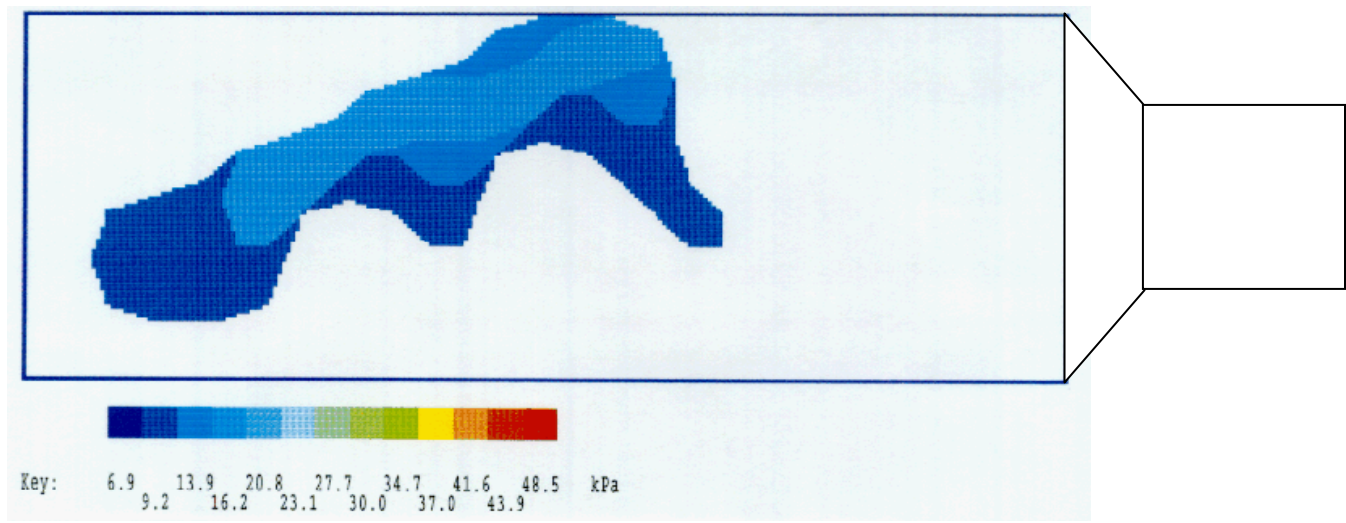
## 3.2 LC Simulator Part 2 - Pressure Measurements

The results of pressure measurements made with the F-Scan™ during the testing of the CTS Prototype Pack K1 system, in the anatomical locations outlined in Section 2.1.7, can be found in Table 3.2. The information presented consists of the average pressure for one recording sample (10 seconds), the peak pressure experienced during this sample, the ratio of peak pressure to average pressure (pressure differential index (PDI)), the force experienced by the wearer in these areas, and the total contact at that location.

**Table 3.2** Pressure measurement results for the CTS Prototype Pack K1. Average and peak pressure results, along with the peak to average pressure differential ratio (PDI) and the contact force and area, are included for one sample period during a dynamic LC Sim trial.

	<b>Average Pressure</b> (kPa)	<b>Peak Pressure</b> (kPa)	<b>PDI</b>	<b>Force</b> (N)	<b>Area</b> (cm <sup>2</sup> )
<b>Anterior Shoulder</b>	13.9	20.8	1.5	47.1	33.9
<b>Posterior Shoulder</b>	10.4	10.4	1.0	5.0	4.8
<b>Upper Lumbar</b>	16.5	21.0	1.3	93.2	56.5
<b>Lower Lumbar</b>	12.8	15.1	1.2	8.3	6.5
<b>Iliac Crest</b>	19.0	22.1	1.2	6.1	3.2

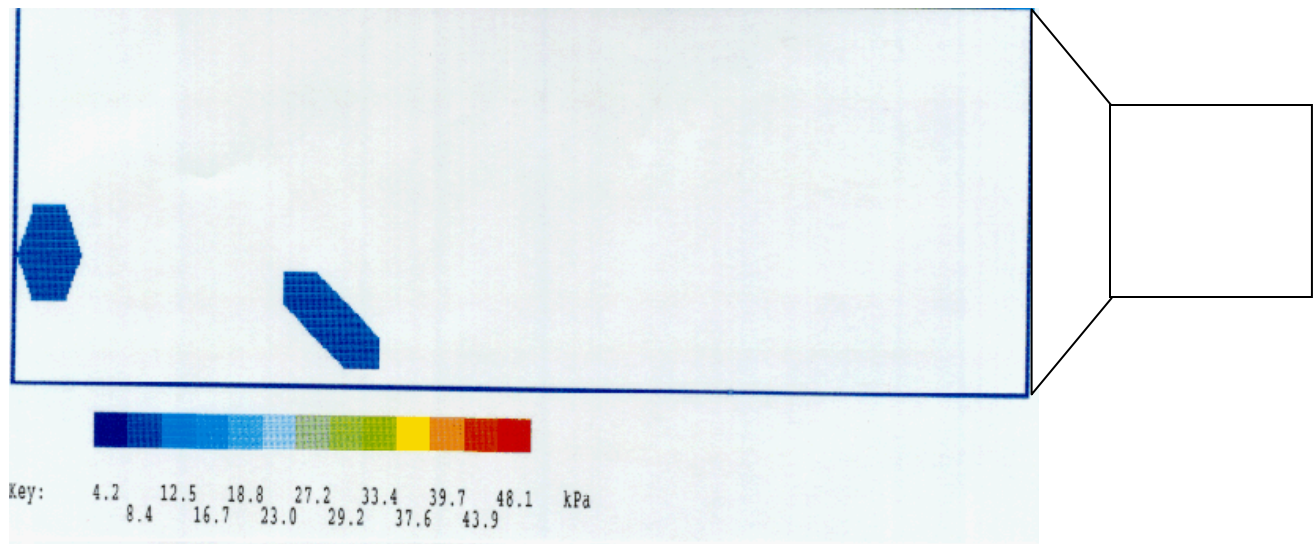
The following sections provide a more detailed breakdown of the pressure response in each anatomical area for testing of the CTS Prototype Pack K1. Note on the pressure sensor maps, the square box on the right hand side represents the long tail on the sensors.



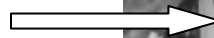
Anterior Shoulder

**Figure 3.2.1.** Pressure map for anterior shoulder.

The peak pressures indicated on the contour plot occurred beneath the attachment point of the load lifter strap on the shoulder pad. The raised pressure portion follows under this 2.5 cm strap across the shoulder.

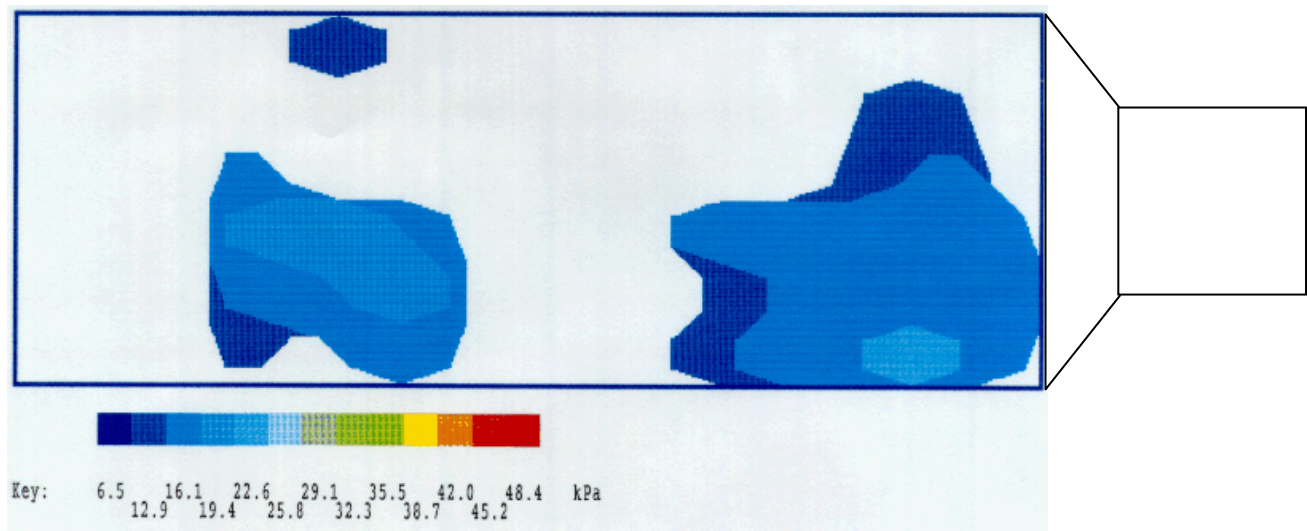


Posterior Shoulder



**Figure 3.2.2.** Pressure map for posterior shoulder.

There was only slight pressure evident due to the contact of the shoulder strap.

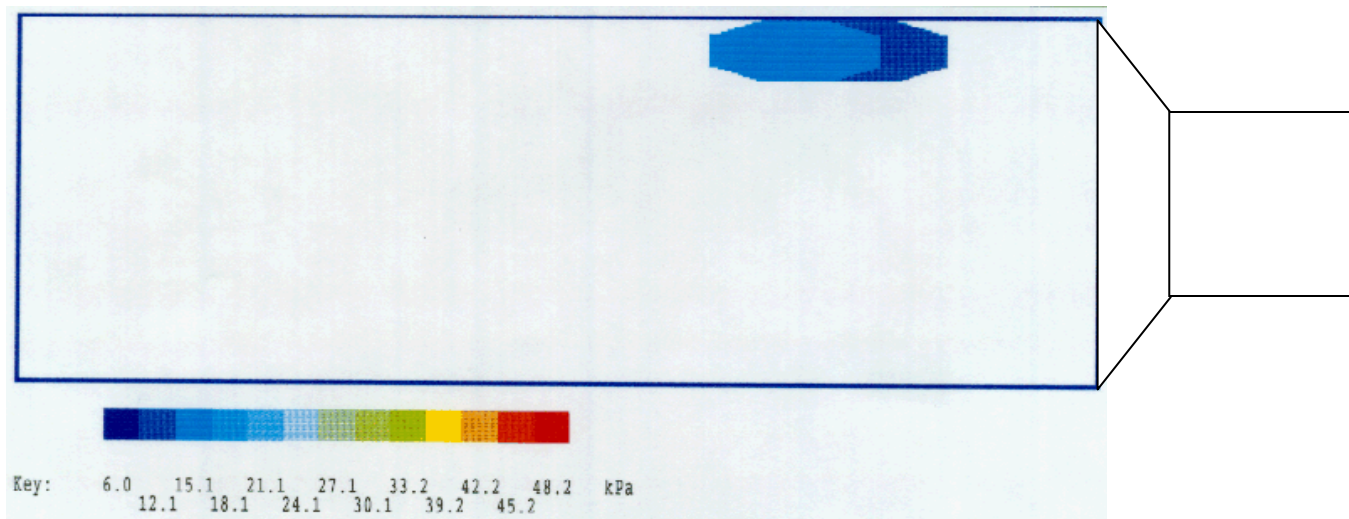


**Figure 3.2.3.** Pressure map for upper lumbar region.

High pressure zones corresponded with the raised portion of the buttocks.

Upper Lumbar



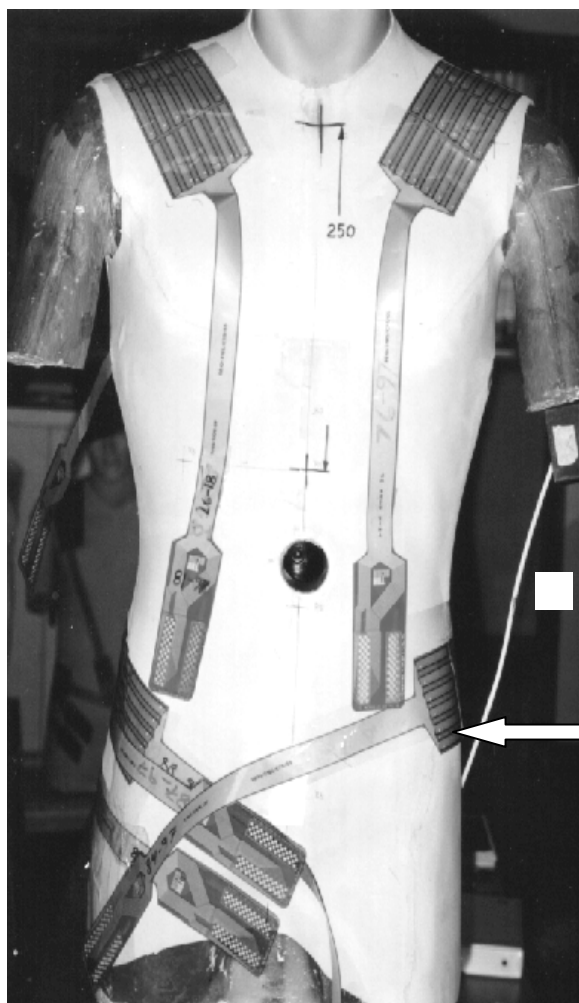
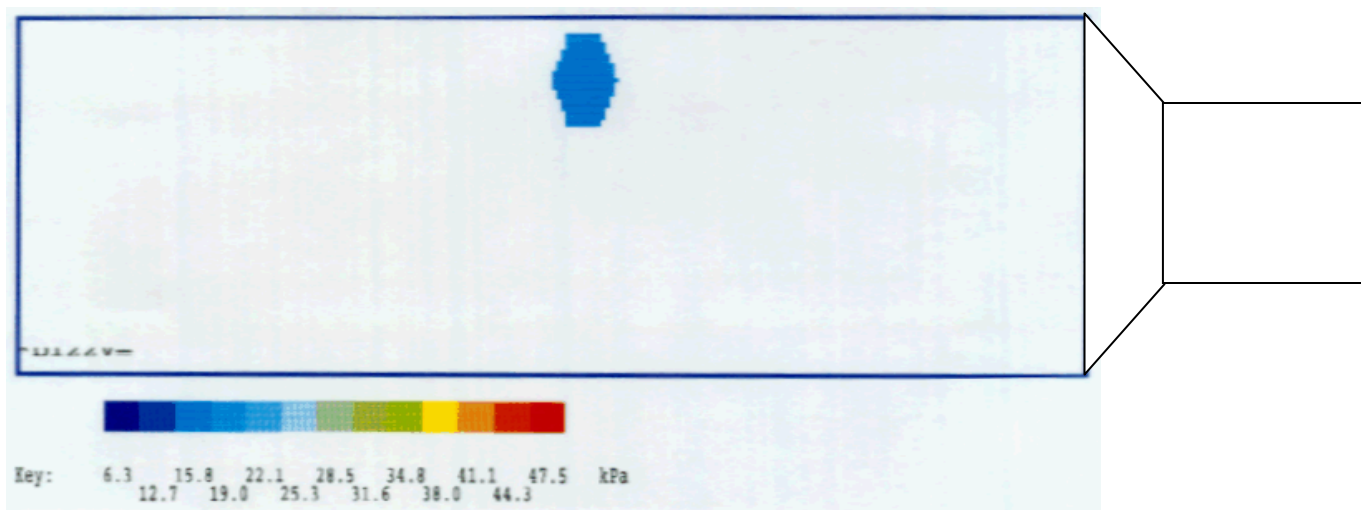


**Figure 3.2.4.** Pressure map for lower lumbar region.

The only pressure evident in this region occurred at the bottom edge of the lumbar padding.

Lower Lumbar





**Figure 3.2.5.** Pressure map for iliac (hip) region.

The peak pressure found on this contour plot was a result of the seam at the top corner of the waist pocket on the combat shirt, which was trapped underneath the hip belt.

Iliac Crest

### 3.3 Compliance - Stiffness Testing

Stiffness testing of the CTS Prototype Pack system was performed in three axes: torsional bending was induced about the z (superior/inferior) axis; lateral bending was induced about the x (anterior/posterior) axis; and forward bending was induced about the y (medial/lateral) axis.

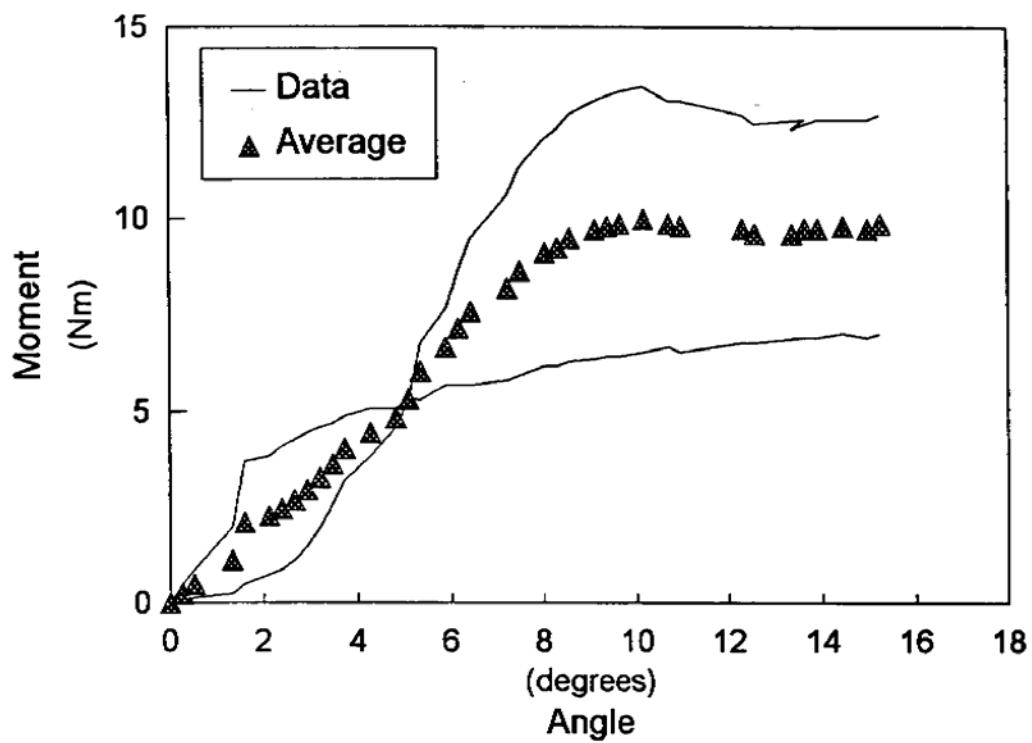
Table 3.3 provides a summary of the LC system stiffness about these three axes.

**Table 3.3** Stiffness and initial resistance values for the CTS Prototype Pack system.

	<b>Torsional Bending</b>	<b>Lateral Bending</b>	<b>Forward Bending</b>
<b>System Stiffness (Nm/θ)</b>	1.16 (from 0° to 8°) 0.04 (from 8° to 14°)	3.30 from 0° to 10°	-0.444 from 0° to 40°

The force-deflection diagrams of the pack in the three directions are shown in Figures 3.3.1, 3.3.2, and 3.3.3 respectively. Of note is the non-linear nature of the response to loading.

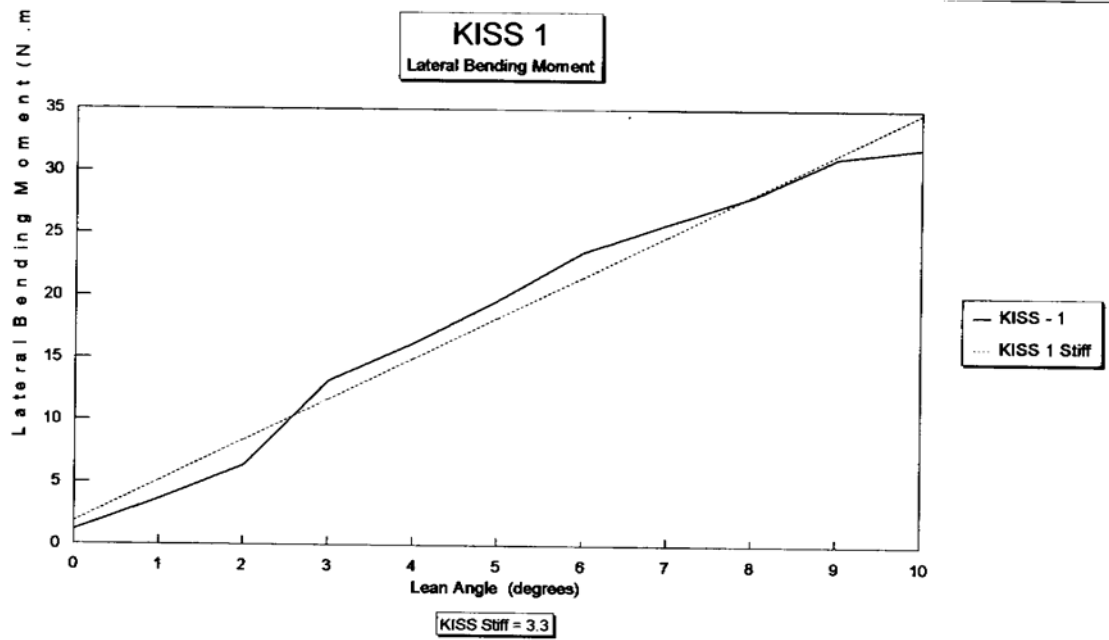
### Torsional Stiffness



**Figure 3.3.1.** Torsional moment as a function of angle.

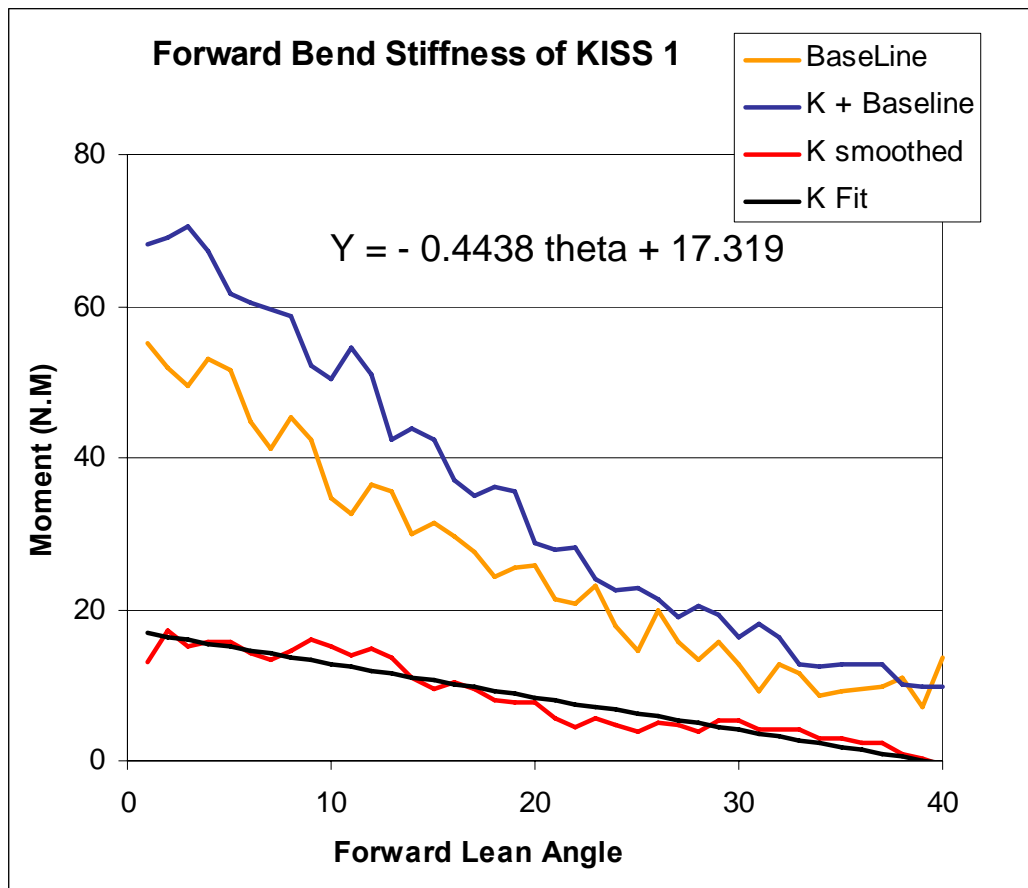
Torsional stiffness is defined as the maximum slope of the graph.

## Lateral Bend Stiffness



**Figure 3.3.2.** Lateral bending moment as a function of angle.

Lateral bending stiffness is defined as the maximum slope of the graph.



**Figure 3.3.3. Forward bending moment as a function of angle.**

Forward bending stiffness is defined as the average maximum slope of the graph., -0.444 N.m/degree of forward bend.

## **4.0 Discussion**

### **4.1 Comparison to Threshold Limit Values**

#### **4.1.1 Average Contact Pressures.**

As yet, no consensus exists regarding an acceptable safe limit for average skin contact pressures at the shoulder, lower back or hip. A maximum value of 14 kPa is recommended for exposures which exceed 8 hours in order to prevent skin necrosis due to blood occlusion. Previous studies by this laboratory have indicated that average contact pressures at the shoulder which exceed 20 kPa will lead to discomfort in the neck and shoulder region in 95% of soldiers. This value is recommended as a threshold limit value for typical load carriage applications.

The CTS Prototype Pack K1 exhibited average pressures which were below the threshold limit for all contact regions except the upper lumbar area. The lone pressure which exceeded the limit was within the range typical of military load carriage systems.

#### **4.1.2 Peak Contact Pressures**

The sensitivity of skin to instantaneous peak pressures varies widely with the nature of the pressure waveform and the region of the body under consideration. A value of 120 kPa is considered to be a conservative threshold limit value for peak pressures in the region of the shoulder, hip and waist.

In no case did the Prototype Pack K1 exhibit pressures which exceeded the threshold limit. The highest value observed, 21.0 kPa, was in the upper lumbar region and corresponded to the relatively high average pressure (16.5 kPa) in this area.

### **4.2 Comparison to Current Benchmarks**

A statistical approach developed under a previous study was used to compare the performance of load carriage systems. The method is based on two steps. In the first, a series of nine load carriage systems were evaluated using the LC simulator and the stiffness tester. The same systems were also evaluated in human factor trials. The correlation between physical

measurements and human factor measurements indicated the objective values which significantly related to soldier load carriage performance acceptability.

In the second step, the benchmark pool was examined to determine the spread of data within any physical measure among the nine packs. The appropriate means and standard deviations were used to establish confidence intervals. In this study, upper and lower deciles ( $\forall = 0.1$ ) were calculated. Thus, a load carriage system with a measured value outside this confidence interval has a likelihood of less than 10% of having performance equivalent to all members of the benchmark pool.

Combining the two steps leads to consideration of the distribution of variables significantly correlated to human factors measures. In this way, the performance of any load carriage system can be meaningfully compared to several systems simultaneously. It also follows that the choice of systems included in the benchmark pool is critical, since an objective is to design a superior device.

#### 4.2.1 Current Benchmark Pool

The current reference data are extracted from a previous study of currently available military load carriage systems. In this particular pool of nine systems, a number of ruck, webbing and vest permutations were examined. The systems were:

- Australian Field Pack Large 1994 with webbing.
- British UK-90 Pack and webbing.
- DACME Packboard with Canadian 1982 webbing.
- DACME Packboard with load carriage vest.
- DACME Packboard with Canadian 1982 webbing and fragmentation vest.
- DACME Packboard with load carriage vest and fragmentation vest.
- Canadian 1982 issue with webbing.
- Canadian 1982 issue with load carriage vest.
- Canadian 1982 issue with webbing and fragmentation vest.

## 4.2.2 Comparison Variables

Significant correlations between LC simulator and stiffness measurements and human factor measurements are indicated in Table 4.2.2. In total, 21 of 39 measurements had significant correlations with  $p < .05$ , including a number of variables which correlated with more than one human factor measure.

**Table 4.2.2** Comparison variables.

Asterisk indicates LC system measurements which are significantly correlated to human factors measurements.

### ***Correlated LC Simulator and Human Factors Measures Displacements and Forces***

<i>LC Simulator Measures</i>		<i>Correlated Human Factors Measurements</i>
<i>Displacement (mm)</i>	x	* Posterior Hip Discomfort
	y	
	z	* Posterior Hip Discomfort
	r	* Posterior Hip Discomfort
<i>Moment (Avg, Nm/kg)</i>	x	
	y	* Forward Flexion Mobility, Overall Comfort, Overall Fit
	z	
	r	
<i>Force (Avg, N/kg)</i>	x	
	y	* Front Mobility, Overhead Mobility, Posterior Shoulder Discomfort, March Thermal Comfort,
	z	* Front Mobility, Overhead Mobility, March Thermal Comfort
	r	
<i>Moment (Amp, Nm/kg)</i>	x	* Torsional Mobility, Overall Mobility, Lie Function, Balance, Agility, Anterior Shoulder Discomfort, March Acceptability, March Comfort
	y	
	z	* Front Mobility
	r	* Posterior Neck Discomfort
<i>Force (Amp, N/kg)</i>	x	
	y	
	z	* Lie Function, Load Control, March Acceptability, March Integration, Overall Balance Overall Comfort, Overall Fit, Overall Maneuverability
	r	* Load Control, March Integration

**Table 4.2.2 (continued)** Comparison variables.

Asterisk indicates LC system measurements which are significantly correlated to human factors measurements.

**Correlated LC Simulator and Human Factors Measures**  
**Pressures and Stiffness**

<i>LC Simulator Measures</i>		<i>Correlated Human Factors Measurements</i>
<i>Shoulder Pressure (ANT)</i>	<i>Av (kPa)</i>	* Posterior Hip Discomfort
	<i>Pk (kPa)</i>	* Doffing Function
	<i>PDI</i>	* Doffing Function
	<i>F (N)</i>	* Posterior Neck Discomfort
<i>Shoulder Pressure (POST)</i>	<i>Av (kPa)</i>	
	<i>Pk (kPa)</i>	* Doffing Function
	<i>PDI</i>	
	<i>F (N)</i>	
<i>Lumbar Pressure (UPPER)</i>	<i>Av (kPa)</i>	
	<i>Pk (kPa)</i>	
	<i>PDI</i>	
	<i>F (N)</i>	* Posterior Discomfort
<i>Lumbar Pressure (LOWER)</i>	<i>Av (kPa)</i>	
	<i>Pk (kPa)</i>	
	<i>PDI</i>	* Front Mobility, Posterior Discomfort
	<i>F (N)</i>	
<i>Stiffness (Nm/deg)</i>	<i>Torsion</i>	* Overhead Mobility, Front Mobility
	<i>Flexion</i>	* Combined Function, Posterior Neck Discomfort, Low Back Discomfort
	<i>Side</i>	* Front Mobility, Anterior Shoulder Discomfort, Anterior Hip Discomfort

### 4.2.3 Benchmark Comparisons

The comparison of test results to the current benchmark pool is shown in Table 4.2.3. In the table, the low decile, mean, and high decile is indicated for each variable. Generally, a low value indicates superior performance, and a high value indicates inferior performance. Exceptions are those values which are normally negative. These are indicated and are treated as absolute values in the analysis. Certain low decile values are unrealistically negative due to the computation methods used. These are treated as zero values for the purposes of analyzing results.

Measurements for the test pack are highlighted. Those measurements falling within high and low decile values are unremarkable and indicate that this parameter is typical of the benchmark pool. Those measurements falling outside the confidence interval are significantly different from the performance of the reference systems and are thus indicating superior or inferior attributes of the test system.

The implication of these results are discussed in terms of design considerations for load control, load transfer, and other factors.

**Table 4.2.3** Comparison of LC system measurements to current bench mark pool.

The low decile, mean, and high decile for each variable is shown. Measurements which lie outside this range are either superior or inferior in comparison to the systems comprising benchmark pool.

**Benchmark Comparisons  
Displacements and Forces**

<b>Ostrom Prototype Pack K1 Results</b>			<b>PERFORMANCE RESULTS</b>					
			Correlated Variable	Superior	Low Decile	Mean	High Decile	Inferior
<i>Displacement (mm)</i>	x	*		<b>1.00</b>	1.32	8.82	12.33	
	y				1.06	3.83	<b>4.10</b>	8.60
	z	*		<b>2.00</b>	7.47	11.32	15.17	
	r	*		<b>4.70</b>	8.16	14.06	19.97	
<i>Moment (Avg, Nm/kg)</i>	x (-ve)			<b>0.10</b>	0.07	-0.07	-0.21	
	y (-ve)	*			-0.13	<b>-0.20</b>	-0.26	-0.39
	z			<b>-0.10</b>	0.01	0.07	0.14	
	r				0.16	<b>0.20</b>	0.30	0.43
<i>Force (Avg, N/kg)</i>	x			<b>6.80</b>	7.06	8.72	10.37	
	y (-ve)	*		<b>-0.20</b>	-1.06	-1.25	-1.44	
	z	*			8.85	8.94	9.03	<b>9.2</b>
	r			<b>11.40</b>	11.49	12.58	13.66	
<i>Moment (Amp, Nm/kg)</i>	x	*			-0.01	0.06	0.13	<b>0.4</b>
	y				0.07	0.32	0.57	<b>1.4</b>
	z	*			-0.01	0.09	<b>0.20</b>	
	r	*			0.11	0.35	0.59	<b>1.5</b>
<i>Force (Amp, N/kg)</i>	x				1.40	3.18	<b>3.50</b>	4.96
	y				-0.19	0.05	0.29	<b>1.1</b>
	z	*			5.41	<b>6.20</b>	7.32	9.22
	r	*			5.91	<b>7.20</b>	8.05	10.18

**Table 4.2.3 (continued)** Comparison of LC system measurements to current bench mark pool.

The low decile, mean, and high decile for each variable is shown. Measurements which lie outside this range are either superior or inferior in comparison to the systems comprising benchmark pool.

**Benchmark Comparison  
Pressures and Stiffness**

<b>Ostrom Prototype Pack K1 Results</b>			<b>PERFORMANCE RESULTS</b>					
			<i>Superior</i>	<i>Low Decile</i>	<i>Mean</i>	<i>High Decile</i>	<i>Inferior</i>	
<i>Shoulder Pressure (ANT)</i>	Av (kPa)	*	<b>13.90</b>	21.78		28.00		34.22
	Pk (kPa)	*	<b>20.80</b>	41.87		72.26		102.66
	PDI	*	<b>1.50</b>	1.63		2.57		3.52
	F (N)	*		43.38	<b>47.10</b>	100.50		157.62
<i>Shoulder Pressure (POST)</i>	Av (kPa)		<b>10.40</b>	13.63		18.94		24.26
	Pk (kPa)	*	<b>10.40</b>	27.01		49.71		72.41
	PDI		<b>1.00</b>	1.34		2.68		4.02
	F (N)		<b>5.00</b>	22.40		73.64		124.89
<i>Lumbar Pressure (UPPER)</i>	Av (kPa)			6.66	<b>16.50</b>	22.57		38.27
	Pk (kPa)			10.12	<b>21.00</b>	55.01		89.90
	PDI		<b>1.30</b>	1.42		2.37		3.32
	F (N)	*		2.10		22.96		43.81
<i>Lumbar Pressure (LOWER)</i>	Av (kPa)			4.65	<b>12.80</b>	30.29		55.93
	Pk (kPa)			-2.39	<b>15.10</b>	84.87		172.12
	PDI	*	<b>1.20</b>	1.32		2.81		4.29
	F (N)			-10.51	<b>8.30</b>	56.52		123.56
<i>Stiffness (Nm/deg)</i>	Torsion	*		0.78	<b>1.16</b>	2.13		3.48
	Flexion	*	<b>-0.444</b>	0.11		0.28		0.44
	Side	*		-1.80	<b>3.30</b>	6.18		14.18

## 4.3 Design Considerations

### 4.3.1 Load Control

#### *Displacement Effects*

The amount of relative displacement between a load and the users body that a LCS suspension system allows, bears directly on the users ability to control the load. Optimally, a load will closely follow the motion of the shoulders while allowing the hips to function with minimal resistance. Following the motion of the shoulders is particularly important during motions requiring large displacements (bending over, ducking under obstacles) or rapid changes in direction. Any large shifting of a heavy load in any direction, quickly becomes difficult for a wearer to restrain. This requirement leads to an upper boundary for the allowable relative displacement of a payload.

In contrast, low amplitude motions such as walking over level ground require different suspension system characteristics. With small displacements and accelerations, the human body is able to easily balance slight shifts in the relative position of the load. In overly stiff suspension systems, the relatively small displacements of the body are still closely tracked, resulting in unnecessary forces on the body. All the accelerations and decelerations of the load will be directly transmitted to a users body. These forces, although not large, are cyclically applied and of very long duration. As a result, they contribute to local muscle fatigue and higher peak contact pressures. This situation leads to a lower boundary for the allowable relative displacement of a payload. LCS suspension systems that restrain a payload more than is necessary, may pay a penalty in user comfort.

The CTS Prototype Pack K1 showed very good control over the relative displacement of the load. It was a superior performer in its control of anterior/posterior and vertical motions. Good displacement control is correlated with reduced posterior hip discomfort.

#### *Stiffness Effects*

The resistance that a LCS offers to motion is related to the human effort required to force that LCS into the required geometry. A tradeoff occurs between the small amplitude motions of

gait and the large motions required for maneuverability. In large magnitude motions, high bending and torsional stiffness work against the user. The user must assume awkward or less stable postures to achieve the range of motion required, thus decreasing their ability to control their load. For small amplitude motions like gait, the stiffness of a LCS may allow it to transfer load effectively to the skeleton and if the range of motion required for gait is not restricted, it will perform well during walking. Therefore, for optimal load control, the combined design elements that provide stiffness to a LCS should constrain the load without constraining a user.

The CTS Prototype Pack K1 showed typical stiffness characteristics in torsion and in lateral bending. It also demonstrated superior forward flexion stiffness which is correlated to good combined functional ratings where large movements are required, reduced posterior neck discomfort and reduced lower back discomfort.

#### 4.3.2 Load Transfer

There are several factors limiting the human body's ability to carry a load. These are: local muscle fatigue caused by unrelieved muscle contraction, transverse shear load through the spine, local contact pressure resulting in the compression of nerves, point pressures on underlying structures, high continuous contact pressures causing compression of underlying tissue and a subsequent inability to oxygenate the tissue.

##### *Forces and moments*

The stiffness elements within a LCS design and the suspension system should serve to transmit the vertical load through the skeleton and onto the spinal column. Any transverse shear load on the spine that is induced by the design is parasitic and can quickly become the limiting factor in load carriage ability. Typically the shoulder girdle and the pelvis are used as the main load transfer sites and are particularly suited for load control and transfer. The average magnitude of the hip reaction force is a direct indicator of the muscle force required by an individual to support this load and LCS. The amplitude of the reaction forces reflect the ability of a LCS suspension system to attenuate the dynamic loading. High amplitudes will require additional muscle forces for load control and a LCS demonstrating high reaction force amplitudes will typically be more energy costly to wear.

The CTS Prototype Pack K1 was an inferior performer with high average vertical reaction forces. It demonstrated superior performance in the anterior/posterior, medial/lateral, and resultant mean reaction forces at the hip. High vertical reaction forces have been correlated with decreased front mobility, decreased overhead mobility, and an increase in marching thermal discomfort.

This LCS showed average vertical and resultant force amplitude characteristics. These factors are correlated to load control, march acceptability, and overall balance performance.

#### *Average pressures*

The average contact pressure in a load transferal region reflects how successful a design is in using the contact site while minimizing the risk of causing tissue damage. Tissue damage may result from continuous compression of underlying tissue and the subsequent inability of the body to oxygenate the tissue. Studies<sup>3</sup> indicate that a safe physiological limit for continuous pressure over 8 hours is 14 kPa, the contact pressure threshold limit for the perception of pain is 20 kPa<sup>4</sup>.

The CTS Prototype Pack K1 showed superior shoulder strap performance with an average contact pressure of 13.9 kPa in the anterior shoulder region. Average contact pressures in the upper and lower lumbar sites were typical at 16.5 and 12.8 kPa respectively. Low average pressure values in the anterior shoulder are correlated with reduced posterior hip discomfort. The average pressure in the iliac crest region also exceeded the threshold value.

#### *Peak pressures*

Large peak pressures reflect pressure concentrations that can lead to bruising or cause tissue damage due to the inability to oxygenate the tissue. Studies have indicated that the tissue tolerance limit for short duration contact pressure (less than 5 minute) is in the order of 120 kPa.

The CTS Prototype Pack K1 showed a significantly low peak pressure (20.8 kPa) at the

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<sup>3</sup> Stevenson, JM., Bryant, JT., Pelot, RP., Morin, EM., Deakin, JM., Reid, SA., Doan, JB., (1997) Research and Development of an Advanced Personal Load Carriage System, Phases II and III, DCIEM Contract # W7711-5-7273/001/TOS.

<sup>4</sup> Holloway, JA., Daly, CH., Kennedy, D., and Chimoskey. (1976) Effects of External Pressure Loading on Human Skin Blood Flow. *Journal of Applied Physiology* **40**: 596-600.

anterior shoulder. Low peak shoulder pressures are related to ease of doffing a LCS. Although the peak and average pressures in the upper lumbar were typical, the large contact area resulted in a large transverse load of 93.2 N. High transverse shear loads are associated with high posterior discomfort in users. This value approaches the threshold limit value for transverse loads on the spine based on achieving optimal human load carriage performance, as determined in a previous study<sup>5</sup>.

## **5.0 Conclusions and Recommendations**

### **5.1 Conclusions**

1. The CTS Prototype Pack K1 pack was compatible with the standardized dynamic testing methods developed to assess military load carriage systems, subject to the reservations noted.
2. Compared to a benchmark pool of nine military load carriage systems testing of the CTS K1 pack indicated superior performance in:
  - a. Control of relative pack-torso motion in the forward and vertical directions,
  - b. Reduced peak pressures effects in the anterior and posterior shoulder, and
  - c. Lower transverse and forward reaction forces at the hip.
3. Compared to a benchmark pool of nine military load carriage systems testing of the CTS K1 pack indicated inferior performance in:
  - a. Higher vertical reaction forces at the hip, and
  - b. Higher lumbar shear forces.
4. The average contact pressure exceeded the threshold limit value expected to cause discomfort in the upper lumbar and iliac crest regions.
5. The transverse force in the lumbar region approaches a value expected to cause discomfort in this area.

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<sup>5</sup> Stevenson, JM., Bryant, JT., Reid, SA., Doan, JB., et al. (1995) Research and Development of an Advanced Personal Load Carriage System, Phases I, DCIEM Contract # W7711-4-7225/01-XSE.

## **5.2 Recommendations**

1. The CTS Prototype Pack K1 should be included in future benchmark data for the design of military load carriage systems.
2. Reasons for high lumbar reaction forces should be studied.

## **6.0 Reservations**

Testing of a rucksack in the absence of battle order is of limited value in the prediction of performance under field conditions. As such, these results should be used as guidelines to design only. Any proposed rucksack should ultimately be tested with suitably designed battle order to determine whole system compatibility.

## **Acknowledgments**

This report is part of the deliverables for Public Works and Government Services of Canada contract # W7711-7-7384/001/SRV and was undertaken in support of design work by Bill Ostrom of Ostrom Manufacturing and Designs Inc. in Nolalu, Ontario. First, I would like to acknowledge the vision of Bill Ostrom who came to listen and learn from speakers at the International Symposium on Military Load Carriage in October 1996 at Queen's University in Kingston, Canada. Since getting to know Bill, our Queen's load carriage team has learned just as much from him. We are kindred spirits in that we just want to design a better system for the soldiers. Thanks Bill.

In addition, I would like to acknowledge Major Linda Bossi from DCIEM who has kept us focused and inspired, and Dr. Ken Ackles who have always believed in our potential to develop better assessment and design-based tools. We appreciate the emphasis and cooperation of Clothe the Soldier Project staff at NDHQ, specifically, LCol Chris Davis and Major Nick Mattern. It remains our belief that the current design-based approach used in this project, where designers are working with the evaluation teams, will lead to the level of understanding needed for an innovative breakthrough in design for future load carriage systems.

The Design Evaluation and Assessment Team (DEAT) for load carriage is comprised of students, staff and faculty from the Clinical Mechanics Group and the Ergonomics Research Group. Our APLCS project manager, Susan Reid continues to advance the LC Simulator's potential to deliver the goods. It is reassuring to know that we can count on you to come through, Sue, and with your usual sense of humor. APLCS assistant manager, Jonathon Doan, has the skills, dedication and ability to stay 'cool' and 'stick handle' through tough spots. Thanks Jon. Also Alan Rigby, our newest addition to the team, has chased down answers to mysterious problems with great thought and understanding. David Siu is a whiz with computers and hardware and Gerry Saunders is always willing to lend a hand. On the faculty side, although Joan Stevenson has been busy with added administrative duties, she is willing to put in late nights with Sue, Jon and I to get things done. Thanks. This has truly been a great team effort where it takes all of us to reach our deliverables on time (well almost on time).

**J. Timothy Bryant, Ph.D., P. Eng. , Coordinator: Clinical Mechanics Group**

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1. Stevenson, JM., Bryant, JT., Reid, SA., Doan, JB., Siu, D., Saunders, G., MacNeil, SK., and C. Barrick.. (1996). Validation of the Load Carriage Simulator: Research and Development of an Advanced Personal Load Carriage System. *DCIEM Contract #W7711-4-7225/01-XSE*.
2. MacNeil, SK. (1996). Validation and development of a mathematical model of the shoulder for load carriage. Master's Thesis, Queen's University, Kingston, ON. (Unpublished).
3. Holloway, JA., Daly, CH., Kennedy, D., and J. Chimoskey. (1976). Effects of external pressure loading on human skin blood flow. . *Journal of Applied Physiology* **40**: 596-600.

## **Annex A**

### **Test Results for CTS Prototype Pack K1**

*Relative Pack-torso Displacement over Ten Seconds.*

*Reaction Forces over Ten Seconds.*

*Reaction Moment over Ten Seconds.*

*Strap Forces over Ten Seconds.*

File: AVIB1A.DAT Test id: Ostrom Prototype Pack #1, Level Walking 1.8 Hz, +/- 25.4 mm

#### Summary of Strap Forces

Time (s)	Shoulder Strap (N)				Waist Strap (N)			
	Avg	Std	Max	Min	Avg	Std	Max	Min
0	78	9	91	65	41	8	46	36
300	79	8	93	65	45	6	50	41
600	79	8	92	64	45	5	49	41
900	79	10	94	64	43	9	47	38
1200	80	8	94	64	43	5	47	39
Trial	79	8	93	64	44	6	48	39

#### Summary of Reaction Forces

Time (s)	Fx (N)		Fy (N)		Fz (N)	
	Avg	Std	Avg	Std	Avg	Std
0	201	47	-6	17	803	266
300	200	47	-6	18	802	263
600	200	47	-6	18	802	266
900	200	46	-7	18	804	267
1200	200	46	-7	18	803	265
Trial	200	47	-6	18	803	265

#### Summary of Reaction Moments

Time (s)	Mx (Nm)		My (Nm)		Mz (Nm)	
	Avg	Std	Avg	Std	Avg	Std
0	2	9	-7	20	-1	8
300	2	8	-6	20	-1	7
600	2	8	-6	20	-1	6
900	2	10	-6	21	-1	10
1200	2	8	-6	20	-1	6
Trial	2	8	-6	20	-1	7

File: AVIB1A.DAT Test id: Ostrom Prototype Pack #1, Level Walking 1.8 Hz, +/- 25.4 mm

#### Range of Reaction Forces

Time (s)	Fx (N)		Fy (N)		Fz (N)	
	Avg	Avg	Avg	Avg	Avg	Avg
	Min	Max	Min	Max	Min	Max
0	108	312	-41	20	335	1231
300	104	315	-46	20	337	1229
600	108	311	-43	20	342	1232
900	109	309	-45	18	333	1235
1200	108	312	-46	20	335	1228
Trial	107	312	-44	20	336	1231

Delta Fx: 204 N

Delta Fy: 64 N

Delta Fz: 895 N

#### Range of Reaction Moments

Time (s)	Mx (Nm)		My (Nm)		Mz (Nm)	
	Avg	Avg	Avg	Avg	Avg	Avg
	Min	Max	Min	Max	Min	Max
0	-7	14	-42	39	-6	2
300	-8	16	-42	40	-6	3
600	-8	16	-41	40	-6	2
900	-7	15	-43	40	-6	2
1200	-8	16	-42	42	-6	3
Trial	-8	15	-42	40	-6	2

Delta Mx: 23 Nm

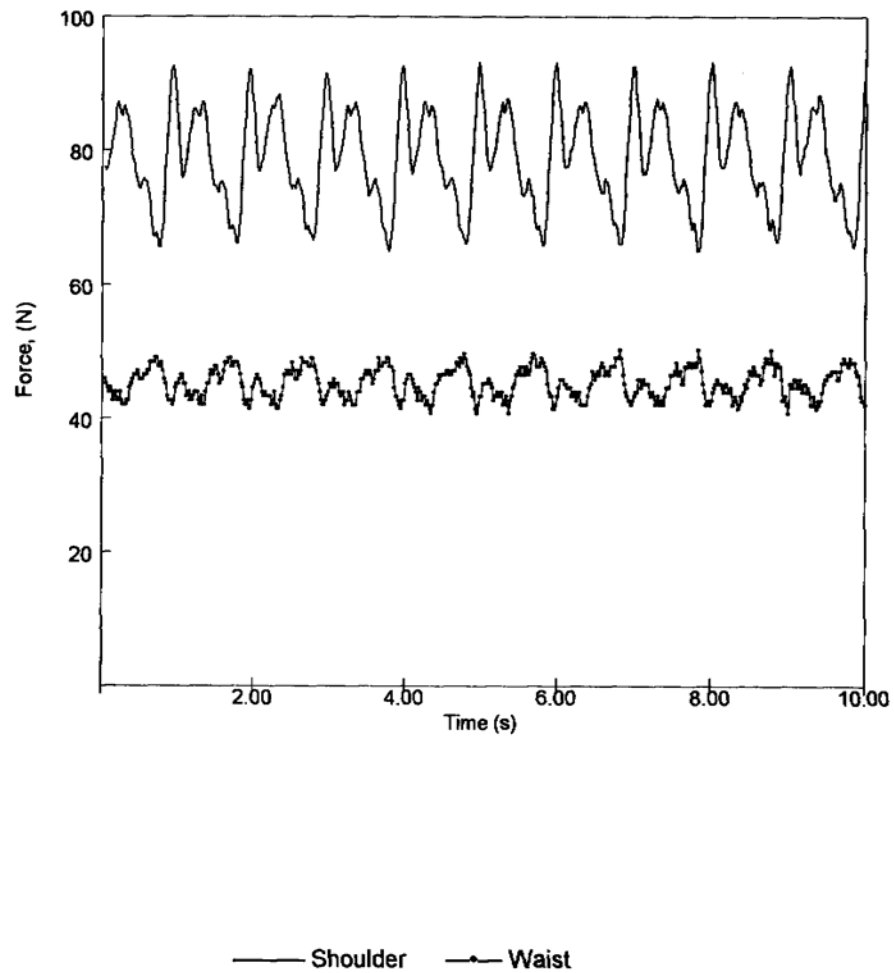
Delta My: 82 Nm

Delta Mz: 9 Nm

## Strap Forces

Ostrom Prototype #1, Level Walking 1.8 Hz, +/- 25.4 mm

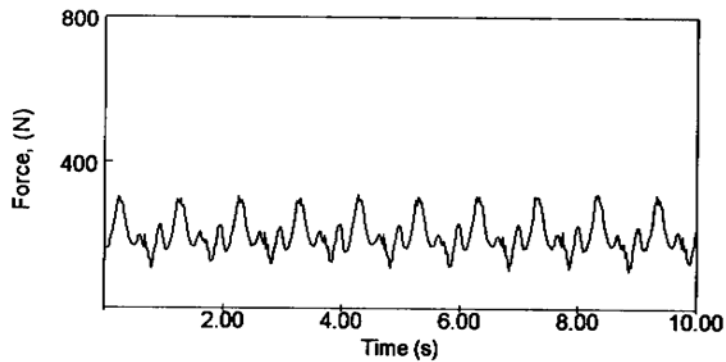
File: av1b1a.dat - Time: 300.0 seconds



## Reaction Forces

Ostrom Prototype #1, Level Walking 1.8 Hz, +/- 25.4 mm

File: av1b1a.dat - Time: 300.0 seconds

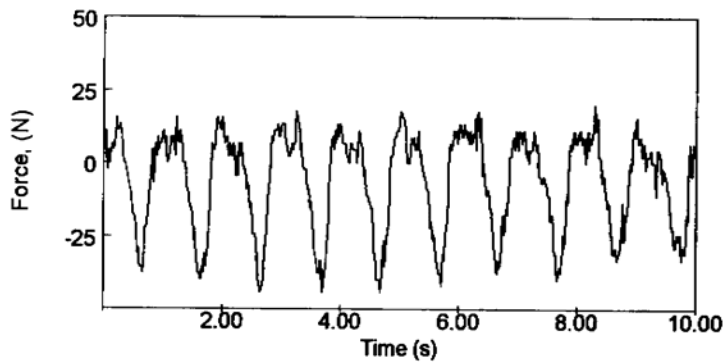


### X Force

anterior/posterior

avg min: 104.0 N

avg max: 315.1 N

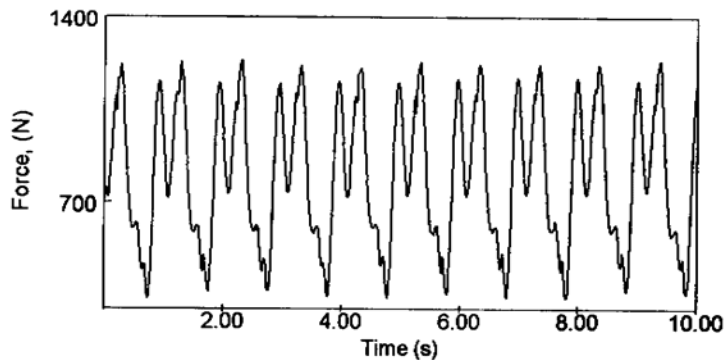


### Y Force

side to side

avg min: -45.6 N

avg max: 20.5 N



### Z Force

vertical

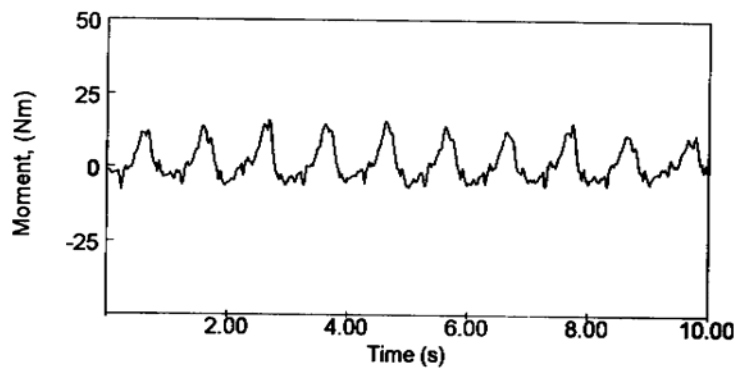
avg min: 337.3 N

avg max: 1229.4 N

## Reaction Moments

Ostrom Prototype #1, Level Walking 1.8 Hz, +/- 25.4 mm

File: av1b1a.dat - Time: 300.0 seconds

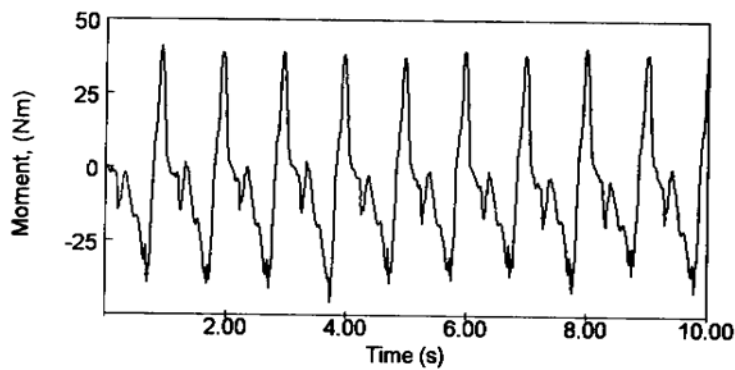


### X Moment

about anterior/posterior axis

avg min: -7.9 Nm

avg max: 15.7 Nm

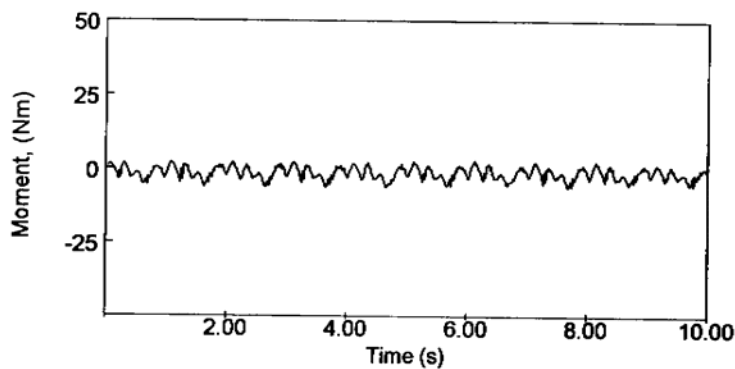


### Y Moment

about side to side axis

avg min: -42.1 Nm

avg max: 40.4 Nm



### Z Moment

about vertical axis

avg min: -6.2 Nm

avg max: 2.7 Nm

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<b>4. AUTHORS</b> (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)  <b>J. M. Stevenson; J. T. Bryant; J. Doan; W. A. Rigby; S.A. Reid</b>		
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- (U) The objective of this study was to conduct a standardized assessment of the Cloth Soldier (CTS) Prototype K1 pack on a computerized Load Carriage (LC) Simulator to assess the load control and load transfer capability of the CTS K1 Pack. These aspects of pack design were comprised of displacement, force, moment and pressure variables that had been validated on previously tested systems where LC Simulator outputs were compared to assessments by experienced users during human trials. A trial consisted of measuring inertial properties and dimensions, loading the pack with a 25 kg payload, and mounting the pack and balancing the moments. Output variables were: three dimensional motions of the pack's center of gravity relative to the person's motion; forces and moments from a 6 degree of freedom load cell at the level of the hips; and average and peak skin pressures and skin forces over the anterior and posterior shoulders, and upper and lower back. To examine the resistance of the pack frame to torso motions in three planes, a pack LC stiffness compliance tester was developed. For load control, the CTS pack K1 ranked as superior in side to side, up and down and resultant (r) relative pack-person motions. All other load control variables were not significantly different from other systems. For load transfer, the CTS K1 pack was inferior for dampening average forces in the vertical direction (z). The CTS Prototype Pack K1 showed typical stiffness characteristics in torsion and in lateral bending. It also demonstrated superior forward flexion stiffness which is correlated to good combined functional ratings where large movements are required, reduced posterior neck discomfort and reduced lower back discomfort.
- (U) Le but de la présente étude était de mener une évaluation standardisée du prototype de sac à dos HLS K1 sur un simulateur de transport de charge informatisé afin d'évaluer la capacité de contrôle et de transfert de charge de ce sac à dos. Ces aspects conceptuels de sac à dos comprenaient des variables de mouvement, de force, de moment et de pression qui avaient été validées sur des systèmes déjà mis à l'épreuve où les résultats du simulateur de transport de charge étaient comparés aux évaluations faites par des utilisateurs expérimentés lors d'essais avec des humains. Un essai consistait à mesurer les propriétés d'inertie et de dimensions avec une charge utile de 25 kg sur le sac à dos, en montant ce sac à dos et en équilibrant ses moments. Les variables de sortie étaient les suivantes : mouvements sur trois dimensions du centre de gravité du sac à dos par rapport aux mouvements de la personne; les forces et les moments par rapport à une cellule dynamométrique tridimensionnelle à 6 degrés de liberté au niveau des hanches; pressions moyennes sur la peau, pressions de crête et forces sur l'avant et l'arrière des épaules, ainsi que le haut et le bas du dos. Pour évaluer la résistance de l'armature externe aux mouvements du torse sur trois plan, on a mis au point une unité de vérification de la conformité de transport de charge. En ce qui concerne le contrôle de la charge, le sac à dos CTS K1 a obtenu une note supérieure pour les mouvements d'un côté à l'autre (x) pour les mouvements verticaux (z) et la résultante (r) pour les mouvements relatifs entre le sac à dos et une personne. Les autres variables de contrôle de charge ne présentaient aucune différence sensible par rapport aux autres systèmes. En ce qui concerne le transfert de charge, le sac à dos K1 s'est révélé inférieur pour amortir les forces moyennes sur le plan vertical (z). Ce prototype de sac à dos K1 HLS a démontré des caractéristiques de rigidité typiques pour la torsion et la flexion latérale. Il a également démontré une rigidité supérieure en flexion vers l'avant qui correspondait à un bon taux de fonctionnalité lorsque des mouvements à

grande amplitude sont nécessaires, ainsi qu'à une réduction de l'inconfort à l'arrière du cou et au bas du dos.

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(U) Load carriage; load carriage simulator; APLCS; Small Pack; pressure measurement system; compliance tester; CTS; clothe the soldier; modular pack

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